Electromechanical efficiency of a deep-well pumping system with a submersible motor; analysis of hydraulic and electrical variables

Eficiencia electromecánica de un sistema de bombeo en pozo profundo, con motor submergible; análisis de las variables hidráulicas y eléctricas

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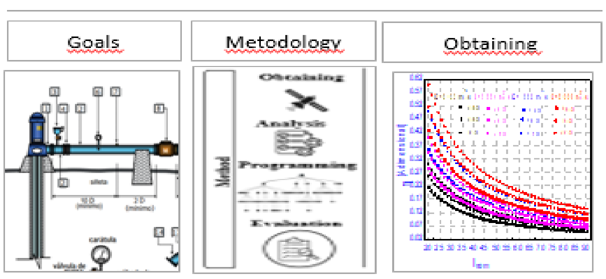
Abstract

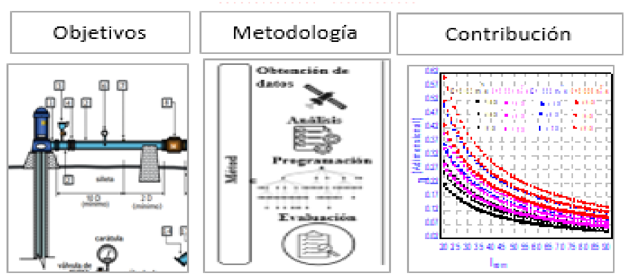
With the EES software, Electromechanical efficiency of a Deep submersible well pumping system in San Francisco de Campeche, Campeche, Mexico, was simulated. Real data from a pumping station were used. It was observed that the highest electromechanical efficiency [ηE] at the same demand current value is obtained at the highest flow rate and highest dynamic head. It was observed that there are almost coincident points for different flow rates and different dynamic heads. This provides important information for an operating engineer controlling the pumping system; they will be able to decide whether to favor a higher dynamic head or a higher flow rate depending on the needs at that moment. This work provides a clear overview of the variables to be controlled in real pumping processes and to achieve the highest possible electromechanical efficiencies with specific variables.



Electromechanical efficiency, Deep submersible well pump, energy saving.

Resumen

Con el software EES se simuló la eficiencia electromecánica de un sistema de bombeo, en San Francisco de Campeche, Campeche, México. Se usaron datos reales de una estación de bombeo. Se observó que la mayor eficiencia electromecánica (η_E) a un mismo valor de corriente de demanda, se obtiene al mayor caudal y mayor altura dinámica . Existen puntos casi coincidentes para diferentes caudales y diferentes alturas dinámicas. Es información importante para un ingeniero operativo que controla el sistema de bombeo; podrá decidir si favorece mayor carga dinámica o mayor caudal según la necesidad de ese momento. El trabajó permite un panorama claro sobre las variables a controlar en procesos reales de bombeo y alcanzar las mayores eficiencias electromecánicas posibles, con variables específicas.



Eficiencia electromecánica, bomba submergible de pozo profundo, ahorro de energí

Area: Development of strategic leading-edge technologies and open innovation for social transformation

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Introduction

Energy efficiency in pumping systems is very important for reducing operating costs and ensuring sustainability in various industries, as well as protecting the environment. Pumping systems often have high energy consumption [usually electrical]; Arun Shankar et al indicate that centrifugal pumps consume up to 20% of the total energy generated worldwide [Arun Shankar et al., 2016], so improving efficiency has a major impact on reducing energy consumption.

Making pumping systems efficient contributes directly to reducing greenhouse gas emissions and the carbon footprint [de Almeida et al., 2003]; it also has an impact on the environmental responsibility objectives of companies and governments [Contreras, 2025]. Koaceli University, Turkey, indicates that 30% of the energy consumed by pumps can be saved through good system design and the selection of appropriate pumps [Kaya et al., 2008]. The most important elements are the motor and the pump [CONAGUA, 2019].

These two elements perform the energy transformation; they must be correctly selected to avoid the lowest percentage of heat or mechanical losses. In three-phase motors, which are the case in this study, the factors that influence losses are the load torque and the stator current [Boglietti et al., 2004]. These factors are particularly detrimental at start-up, when energy consumption is at its highest during operation. Spanish research on irrigation pumps proposes a sequential pump activation system to make the hydraulic system more efficient [Moreno et al., 2007]. In Mexico, this issue has great potential to improve energy efficiency and reduce costs in key sectors such as agriculture and water management.

The implementation of advanced technologies, proper maintenance, and optimal system design are fundamental strategies for achieving these objectives [Hector Camacho, 2017]. The Mexican Institute of Water Technology [IMTA] has conducted studies in the agricultural sector. They have identified opportunities to improve energy efficiency through proper pump selection. However, this is not enough to achieve an efficient system [Lobato Sánchez & Mejía Estrada, 2021]. Studies carried out by the National Commission for the Efficient Use of Energy [CONUEE] have explored the efficiency of pumping systems.

They recommend the implementation of advanced technologies, as well as continuous monitoring, which can reduce energy consumption by 15% to 30% [National Commission for the Efficient Use of Energy, 2011]. A study conducted in the Mezquital Valley, Hidalgo, evaluated the energy efficiency of pumping systems used for irrigation, identifying opportunities for energy savings through the optimisation of pumping system design [CONAGUA, 2016] [CONAGUA, 2019]. In this study, with the help of EES software, the electromechanical efficiency of a deep well pumping system with a submersible motor was characterised in order to optimise the electrical system.

1. The evolution of pumping systems.

The development of water transport systems covers many technological and scientific developments that have evolved over time to meet the needs of societies for water supply, distribution, treatment and management. From the earliest civilisations to modern systems, water transport has made significant advances. Early societies settled near water sources [rivers, streams or springs], creating the first rudimentary water transport and distribution systems. These generally consisted of simple canals or ditches to direct water from its source to populated areas. Early water systems relied on gravity, which often made them inefficient because they depended on natural flow. It was not until the advent of the industrial revolution that the first hydraulic pumps were introduced. Figure 1.

Box 1

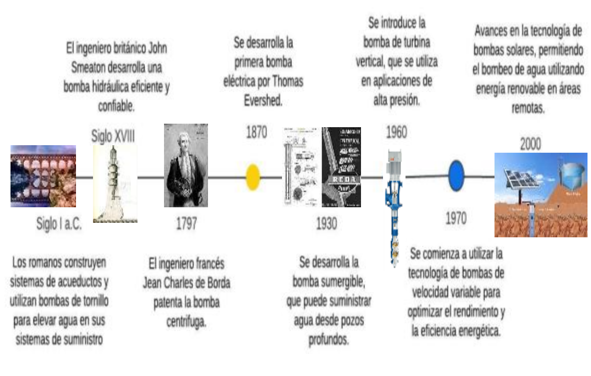

Figure 1
Timeline of the development of water transport, from ancient civilisation to the contemporary era.

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2 Components of a pumping system.

Extracting groundwater through deep wells to provide drinking water to communities is an important global issue, according to Agenda 2030, signed by several countries of the United Nations [UN]. It is the sixth goal, which aims to achieve universal and equitable access to drinking water [ASF, 2020].

In addition to the correct identification of the aquifer and the efficiency and safety of the deep well, it is also important to select and install its constituent elements appropriately [Driscoll F.G., 2007]. We classify these components into two types: mechanical and electrical. Both are essential for the operation of the well.

2.1 Mechanical elements

A mechanical element is defined as a part or component used in mechanical systems to transmit motion, force, or energy [Secretariat of Energy, 2015]. They ensure the effective functioning of several parts together. They serve different purposes: to support and guide loads, reduce friction, and join other parts.

2.1.1 The pump

This is one of the most important elements in a PPMS, providing the energy needed to transport the fluid to a higher point. At great depths, greater pumping pressure is required to transport the water to its final destination. Without a pump, it would be impossible for the water or fluid to rise naturally. There are different types of pumps; they are designed according to their function and operating conditions. Figure 2 shows a general classification of these according to CONAGUA.

Box 2

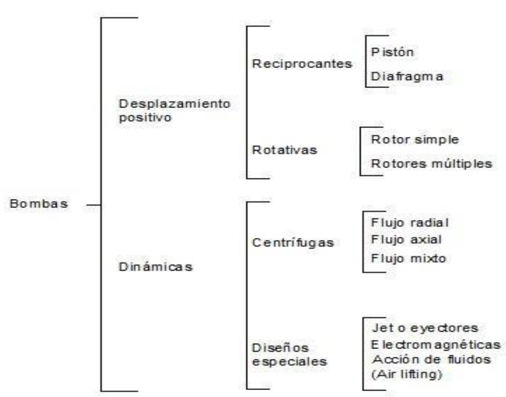

Figure 2
Classification of pumps according to NOM CONAGUA.

The pumps used in PPMS are also called bowl bodies [Department of Energy, 2015] [Sosa et al., 2005], because they are made up of concave elements that contain the impellers inside. Each bowl increases the fluid pressure to overcome a total dynamic load [Secretariat of Energy, 2015], Figure 3.

Box 3

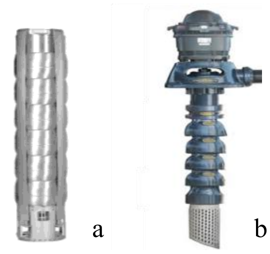

Figure 3
[a] Stainless steel bowl body [b] Turbine-type bowl body.

2.1.2 Pump column.

This element is a set of pipes connecting the submersible pump to the discharge train [Driscoll F.G., 2007], Figure 4, which represents a pumping column for a PPMS. The length of the pumping column depends on the construction characteristics of the well: depth, capacity, water table, well recovery time, casing and pump discharge [Secretariat of Energy, 2015] [Driscoll F.G., 2007]. The diameter of the pumping column depends on the flow rate delivered by the pump [BREIER, 2006][López, n.d.].

Box 4

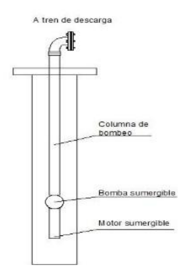

Figure 4
PPMS pumping column.

2.1.3 Unloading train.

All pumping systems have elements for controlling, monitoring, and measuring their operation. These are known as the discharge train. Figure 5. This is a set of valves and instruments installed in the discharge pipe of a PPMS. Each element of the train has a specific function.

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Box 5

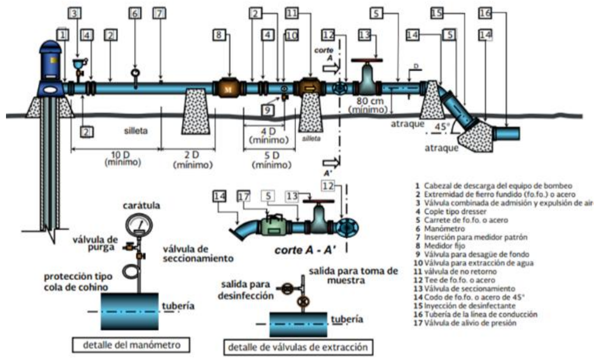

Figure 5

Deep well discharge train with submersible pump with external motor.

2. Hydrodynamics of a Deep Well with Submersible Motor

Electromechanical efficiency in deep wells is becoming increasingly important in modern engineering. It has a direct impact on the optimisation of energy resources and the sustainability of water extraction operations.

These wells combine hydraulic and electrical components, which require comprehensive analysis to maximise their performance. Among the hydraulic variables, we can mention: flow rate [Q], the volume of fluid moved per unit of time; fluid density [ρ], which affects the hydraulic load; gravity [g], which influences the potential energy of the system; and load losses, which represent the dissipation of energy due to friction and other factors in fluid conduction [Sosa et al., 2005] [BREIER, 2006]. On the other hand, the electrical variables are: current [I], voltage [V] and power factor [PF], which are decisive in the efficiency of the submersible motor; they define energy consumption and the capacity to convert electrical energy into mechanical energy [Pechenik et al., 2019].

The way these variables interact describes the overall efficiency of the system. Previous studies highlight the importance of proper design and continuous monitoring to minimise losses and ensure efficient operation [Pechenik et al., 2019] [Vaschetti et al., 2012] [Secretaria de Energia, 2016].

This paper presents an analysis of the electromechanical efficiency in deep wells with submersible motors, with the help of ees software, taking into account a multidisciplinary approach that integrates principles of hydraulics and electrical engineering.

3. Electromechanical efficiency

The importance of a Deep Well with Submersible Motor [PPMS] lies in its ability to provide groundwater for both human consumption and various industrial and agricultural uses. Consequently, during the design stage, consideration must be given not only to its construction, but also to its correct operation, as well as the projection of its future costs for maintenance and electricity consumption.

Operating costs are evaluated for a well life of 20 years [Mala-Jetmarova et al., 2018]. Studies by the Mexican government indicate that 30% of electrical energy can be saved with good system design and the choice of appropriate pumps [Agriculture|dgsiap, 2024]. Although the pumps are highly efficient, this alone is not enough for a pumping system to operate at maximum efficiency [Agricultura|dgsiap, 2024].

Therefore, it is necessary to properly design the entire Submersible Motor Pumping Station [EBMS] installation to achieve adequate electromechanical efficiency. The electromechanical efficiency of an EBMS is defined as the ratio between the power transmitted to the fluid [pump output power] and the power input to the pump [motor input power]. This ratio is represented in equation 1 [Secretaría de Energía, 2015].

$$\eta_E = \frac{P_S}{P_e} = \frac{\textit{Potencia de salida de la bomba}}{\textit{Potencia de entrada al motor}} \qquad [1]$$

Power values are given in kilowatts [kW]; the efficiency value is dimensionless. To determine the electromechanical efficiency value, variables involved in equation 1, both hydraulic and electrical, must be taken into account.

3.1 Hydraulic variables.

3.1.2 Flow rate [Q]

The amount of water flowing through the cross-section of a pipe in a given period of time is defined as flow rate or discharge, expressed in m^3/s [Secretariat of Energy, 2015].

Different methods or instruments can be used to measure flow rate, which will give an approximate value of the actual rate.

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3.1.2 Fluid density.

For flow rate, an important physical property must be taken into account: density. This is a critical factor in pump selection. Density is defined as the unit of mass per unit of volume [kg/m³] occupied by the fluid. For water, the density value is 1,000 kg/m³ [Secretariat of Energy, 2015].

3.1.3 Gravity [g]

Gravity influences the height to which a pump can lift the liquid. The maximum lift height is determined by the pump's ability to overcome the resistance of gravity while pumping the liquid upwards.

3.1.4 Total dynamic head [H]

This parameter is the algebraic sum of the gauge pressure measured at the discharge [converted to metres of water column and corrected for the height to the centre line of the pressure signal intake], the dynamic level, the friction losses in the column and the velocity head. Its mathematical expression is given by equation 2 [Secretaría de Energía, 2015][Otto Caro Niño, 2025].

$$H = P_{gd} + Z_d + h_{fc} + h_v \qquad [2]$$

Where:

H *Total pumping load [m.c.a]*
P_{gd} *Pressure at discharge, [m.c.a]*
Z_d *Dynamic level [m.c.a]*
H_{fc} *Friction losses [m.c.a]*
H_v *Speed load [m.c.a]*

The above parameters represent the power supplied to the fluid and converge in equation 3 [Secretaría de Energía, 2015].

$$P_s = Q\rho g H \qquad [3]$$

Where:
P_s *Pump output power [kW]*
Q *Flow rate [m³/s]*
G *Acceleration due to gravity, 9.81 [m/s²]*
H *Total dynamic load [m.c.a]*

3.2 Electrical variables of the input power to the motor.

The variables involved in the motor input power in the study of electromechanical efficiency are: voltage, current, and power factor.

3.2.1 Voltage [V]

The importance of the potential differential in a three-phase motor lies in the fact that it determines the speed and output power of the motor. An adequate voltage profile provides information about the stability of the power supply and is crucial for keeping the electrical system operating safely [Vaschetti et al., 2012]. In an EBMS, submersible motors operate at a voltage of 220/440 V three-phase system.

3.2.2 Current [I]

The electrical current consumed by a motor in an EBMS is directly related to the energy it uses.

The higher the current, the higher the energy consumption. According to some estimates from global practice, electricity consumption by pumping systems varies from an average of 20 to 50% of their global production [Pechenik et al., 2019]. Various instruments can be used to measure this, such as an electrical network analyser or a clamp ammeter.

3.2.3 Power factor [PF]

An indicator used to measure the degree of electrical efficiency in a system. It is a ratio of the actual power flowing to the load and the apparent power in the circuit; it ranges from 0 to 1 ['IEEE Standard Definitions for the Measurement of Electric Power Quantities Under Sinusoidal, Nonsinusoidal, Balanced, or Unbalanced Conditions,' 2010] [Warne, 2005]. A low PF represents energy losses in the system and results in penalties from the electricity supplier [CFE in Mexico]. The official CFE website states that users must maintain a PF as close to 100% as possible; if the PF is <90%, the supplier will charge the user the amount resulting from applying the surcharge percentage to the bill. If the PF is greater than 90%, the supplier will be obliged to give the user a credit [ELECTRICIDAD, 2025].

When performing an energy balance, we know that, in any system, there will be incoming energy, which, in the case of an EBMS, is electrical energy. Therefore, the input power to the motor [P_e] is defined by 4 [Secretaría de Energía, 2015].

$$P_e = \sqrt{3} VIFP \qquad [4]$$

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Where:
V *Potential difference [V]*
I *Current [A]*
FP *Power factor [dimensionless]*

Substituting equations 3 and 4 into equation 1, we obtain equation 5:

$$\eta_E = \frac{P_S}{P_e} = \frac{Q\rho gH}{\sqrt{3}VIFP} \qquad [5]$$

This is the equation that represents electromechanical efficiency, taking into account mechanical and electrical parameters.

Methodology

The methodology used in this study was as follows: actual values were considered in a well in the city of San Francisco de Campeche, Campeche, Mexico. First, a constant volumetric flow of water of 0.005 m^3/s was considered, with a density of 1000 kg/m^3 at 25 to 30 °C, earth's gravity of 9.81 m/s^2, and a constant total dynamic height of 60 m. Furthermore, it was assumed that the potential difference of the electric motor remained constant at 220 V and the power factor at 0.9 [dimensionless].

- Initially, the electromechanical efficiency of the deep well pumping system was characterised with the help of EES software, using the above values. The flow was kept constant and the current was modified.

- The electromechanical efficiency of the pumping system was characterised parametrically by modifying the expenses and currents.

- The electromechanical efficiency of the pumping system was characterised parametrically for four representative expenses and by modifying the operating currents.

Results

We worked with real values in a well in the city of San Francisco de Campeche, Campeche, Mexico. The operation of the pumping system was simulated using EES software. Initially, a constant volumetric flow of water [0.005 m^3/s] was considered with a three-phase submersible pump at 220VC, and the motor's consumption current was varied. The results are shown in Figure 6.

Box 6

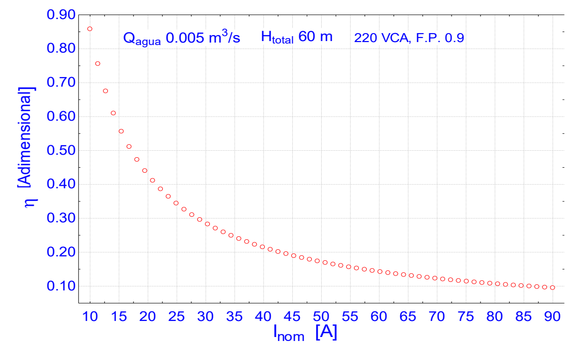

Figure 6
Electromechanical efficiency of a pumping system with a constant flow rate [0.005 m3/s] and varying current consumption.

Similarly, the operation of the pumping system was simulated [EES software] parametrically by varying the flow rate for different current demand values and keeping the total dynamic load constant. Figure 7.

Box 7

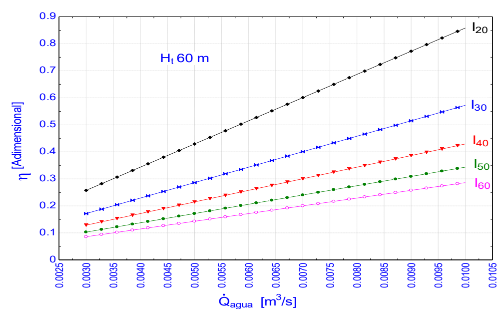

Figure 7
Electromechanical efficiency of a pumping system with different flow rates and different consumption currents.

Similarly, the operation of the pumping system was simulated [EES software] parametrically by varying the demand current for four different dynamic head values and keeping the flow rate constant. Figures 8 and 9.

Box 8

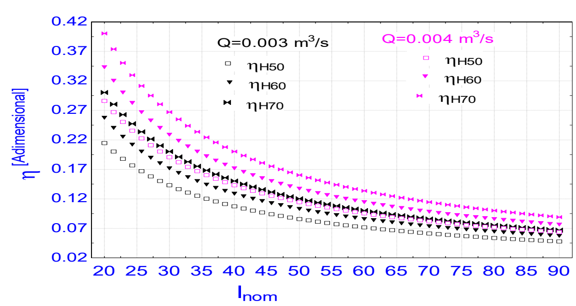

Figure 8
Electromechanical efficiency of a pumping system for three dynamic heights [H, 50, 60, 70] and flow rates [Q, 0.003, 0.004] when varying the demand current.

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Box 9

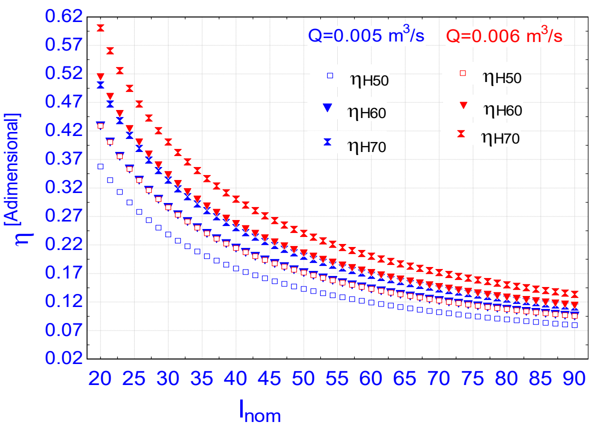

Figure 9

Electromechanical efficiency of a pumping system for three dynamic heights [H, 50, 60, 70] and flow rates [Q, 0.005, 0.006] when varying the demand current.

Conclusions

With the help of EES software, the electromechanical efficiency of a pumping system with a constant flow rate [0.005 m^3/s], a typical value for this type of pumping system, was simulated.

The current consumption was varied to simulate all the characteristics of the system in the city of San Francisco de Campeche, Campeche, Mexico, as shown in Figure 6. This served as a frame of reference to ensure that the results were consistent with the actual situation in San Francisco de Campeche, Campeche, Mexico. A three-phase submersible pump at 220VC was considered, discharging at a dynamic height of 60 m, and the motor consumption current was varied.

From Figure 7, we can see that for a deep well pumping system with the same flow rate and dynamic height of 60 m [typical value for a well in San Francisco de Campeche], we can obtain different electromechanical efficiencies by varying the demand current. In engineering practice, this graph provides information for selecting preferably high-efficiency pumps or for having a clear idea of the operating amperage limit, in order to seek options for reducing the amperage demand. For example, using frequency converters, increasing pipe diameter, internal pipe coatings, among others. We can even identify which amperage values cannot be found on the pump market, as they represent idealised cases.

From Figure 8, we can see that the highest electromechanical efficiency at the same demand current value, 20 A, is obtained at the highest flow rate [0.004 m^3/s] and highest dynamic head [70 m]. If we analyse each of the current values, at the same value we will always have the highest efficiency at the highest flow rate and dynamic head; however, we can also see that there are almost coinciding points for different flow rates and different dynamic heads in the centre of the graph. The efficiency with Q of 0.003 and dynamic head of 70 is very similar to the efficiency with Q of 0.004 and dynamic head of 50.

From Figure 9, we can see that the highest electromechanical efficiency at the same demand current value of 20 A is obtained at the highest flow rate [0.006 m^3/s] and highest dynamic head [70 m], as we also see in Figure 8. If we analyse each of the current values, at the same value we will always have the highest efficiency at the highest flow rate and dynamic head; however, we can also see that there are almost coinciding points for different flow rates and different dynamic heads in the centre of the graph.

The latter is very important for an operational engineer who is controlling the pumping system, because at the time they will be able to decide whether to favour greater dynamic head or greater flow rate according to the needs at that moment; it should be noted that pumping is often not constant and must be adapted to the needs of demand.

A more general overview is presented in Figure 10, combining the values from Figures 8 and 9.

Box 10

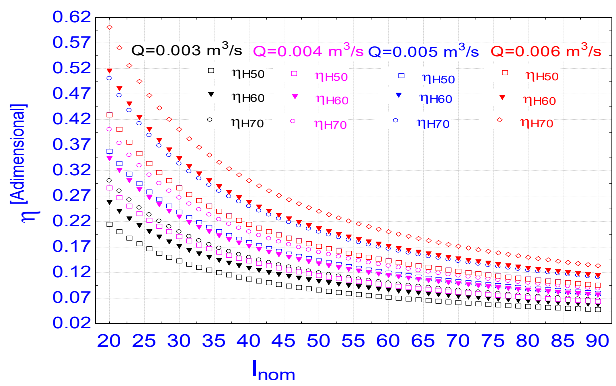

Figure 10

Electromechanical efficiency of a pumping system for three dynamic heights [H, 50, 60, 70] and flow rates [Q, 0.003 to 0.006] when varying the demand current.

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We believe that this simulation tool provides a clear overview of the variables to be controlled in real pumping processes, thereby achieving the highest possible electromechanical efficiencies in processes with specific variables. We identify the theoretical operating limits [lower and upper] of the systems.

Declarations

Conflict of interest

The authors declare no conflict of interest. They have no known competing financial interests or personal relationships that could have appeared to influence the article reported in this article.

Author contribution

Chan-González, Jorge de Jesús: contributed to the development of the EES simulation of the mathematical model of electromechanical efficiency and the generation of the respective graphs, as well as the drafting of the document.

Pech-Flores, Juan Manuel: contributed to the idea for the research project on the method and research on the mathematical model, as well as the drafting of the paper.

Lezama-Zárraga, Francisco Román: contributed to the revision of the writing, spelling and style editor, as well as the revision of the results obtained by the simulation.

Shih, Meng Yen: contributed to the revision of the writing, spelling and style editor, as well as the revision of the results obtained by the simulation, supervision of the method and research of the mathematical model, and the writing of the paper.

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Abbreviations

CFE	Federal Electricity Commission
CONAGUA	National Water Commission
CONUEE	National Commission for the Efficient Use of Energy
EBMS	Submersible Motor Pumping Station
EES	Engineering Equation Solver
IMTA	Mexican Institute of Water Technology
NOM	Official Mexican Standard
ONU	United Nations
PPMS	Deep Well with Submersible Motor

Variables

FP	Power factor	dimensionless
g	Earth's gravity	m/s^2
H	Dynamic height	m
I	Current	A
P_e	Motor drive power	kW
Q	Flow rate	l/s
V	Voltage	V

Greek letters

η_E	Electromechanical Efficiency	dimensionless
ρ	Density	kg/m^3

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Basic

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